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14. ABSTRACT

The University of Florida (UF) and Florida Institute of Technology (FIT) completed an exploratory (seedling) program that examined the salient aspects of lightning initiation and propagation including the role of X-rays, gamma rays, and cosmic rays in the initiation and propagation of lightning and in the phenomenology of thunderclouds. The experimental portion took place at the International Center for Lightning Research and Testing (ICLRT) in north-central Florida.

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Lightning, protection, X-rays, gamma rays

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Abstract

Working at the International Center of Lightning Research and Testing at Camp Blanding, FL during Summer and Fall 2009, the University of Florida/Florida Institute of Technology team has acquired high speed optical, wideband electric and magnetic field, and x-ray data on triggered and natural lightning and on natural lightning initiation. Among the new results obtained are:

(1) Source locations for lightning leader dE/dt and x-ray emissions with meter-scale accuracy using a 10 station time-of-arrival network;

(2) High speed video images at frame times as short as 3 μs, showing the development of the upward positive leader in triggered lightning and of the downward negative dart-stepped leader preceding return strokes;

(3) Measurement of the electric field at two stations on the ground 60 m and 350 m from the launch site during rocket-and-wire ascension, allowing probing of the vertical electric field profile at the time of launch;

(4) Design and construction of a prototype pin-hole x-ray camera for imaging lightning x-ray sources;

(5) Design and construction of an rf pulse detector for measuring the radiation from cosmic-ray-induced runaway electrons in high thunderstorm electric fields.

"Lightning Initiation and Propagation"

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I. Introduction

DARPA Grant W31P4Q-09-1-0018 is primarily involved with (1) acquiring high-speed optical, wideband electric and magnetic field, and x-ray data on triggered and on natural lightning and natural lightning initiation at the International Center for Lightning Research and Testing during Summer and Fall 2009 and (2) analyzing, modeling, and writing journal and conference papers concerning these data and data acquired under the previous DARPA Grant HR0011-08-1-0088.

II. Publications

The following journal papers and conference papers are associated with the Grant. Some of these papers were begun under the previous Darpa Grant HR0011-08-1-0088, the two grants having overlapped during Summer 2009. These papers contain the detailed results of the Darpa-funded research.

<u>Journal Papers</u>

1. Properties of the x-ray emission from rocket-triggered lightning as measured by the Thunderstorm Energetic Radiation Array (TERA), J. Geophys. Res, Vol. 114, D17210,doi:10.1029/2008JD011618, 2009, Z. Saleh, J. Dwyer, J. Howard, M. Uman, M. Bakhtiari, D. Concha, M. Stapleton, D. Hill, C. Biagi and H. K. Rassoul
2. Remote measurements of thundercloud electrostatic fields, J. Geophys. Res., 114, D09208, doi:10.1029/2008JD011386, J. R. Dwyer, M. A. Uman, and H. K. Rassoul
3. Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, J. Geophys. Res., Vol. 115, accepted for publication, J. R. Dwyer, D. M. Smith, M. A. Uman, Z. Saleh, B. Grefenstette, B. Hazelton, and H. K. Rassoul
4. High-speed Video Observations of Rocket-and-Wire Initiated Lightning, Geophys. Res. Let., Vol.36, L15801, doi:10.1029/2009GL038525, 2009, C. J. Biagi, D. M. Jordan, M. A. Uman, J. D. Hill, W. H. Beasley, and J. Howard
5. RF and x-ray source locations during the lightning attachment process, J. Geophys. Res., Vol. 115, D06204, doi:10.1029/2009JD012055, 2010, J. Howard, M. A. Uman, C. Biagi, D. Hill, V. A. Rakov, Z. Saleh, H. Rassoul
6. On phenomenology of compact intracloud lightning discharges, J. Geophys. Res., Vol. 115, 2010, in press, A. Nag and V. A. Rakov
7. Some inferences on the role of positive charge region in facilitating different types of lightning, Geophys. Res. Lett., 36,L05815,2009doi:10.1029/2008GL036783, A. Nag, and V. A. Rakov
8. Electromagnetic pulses produced by bouncing-wave-type lightning discharges, IEEE Trans. on EMC, Vol. 51, No. 3, pp. 466-470, August 2009, A. Nag and V. A. Rakov
9. Three-dimensional imaging of upward positive leaders in triggered lightning using VHF broadband digital interferometers, Geophys. Res. Lett., 37, L05805, doi:10.1029/2009GL042065, 2010, S. Yoshida, C.J. Biagi, V.A. Rakov, J.D. Hill,

M.V. Stapleton, D.M. Jordan, M.A. Uman, T. Morimoto, T. Ushio, Z.-I. Kawasaki

10. Electric and Magnetic Fields Predicted by Different Electromagnetic Models of the Lightning Return Stroke Versus Measured Fields, IEEE Trans. on EMC, Special Issue on Lightning, Vol. 51, No. 3, pp. 479-487, August 2009, Y. Baba and V.A. Rakov
11. Analysis of microsecond-and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges, Atmos. Res., 91, 2009, 316-325, A. Nag, B. DeCarlo, and V.A. Rakov

Conference Papers (presented at a conference orally or via poster, with published Abstracts)

1. Characterization of X-ray Emission from Natural and Rocket-and-Wire Triggered Lightning, EOS Transactions AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE33B-0303, Z. H. Saleh, J. R. Dwyer, H. Rassoul, M. Schaal, E. S. Cramer, J. D. Hill, C. J. Biagi, D. M. Jordan, M. V. Stapleton, M. A. Uman
2. Optical Spectra of Triggered Lightning, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 15, 2009, ID No. AE21A-0297, T.D. Walker, C. J. Biagi, J. D. Hill, D. M. Jordan, M. A. Uman, H. J. Christian, Jr.
3. Rocket-triggered Lightning Observed by VHF Broadband Digital Interferometers, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 15, 2009, ID No. AE21A-0298, S. Yoshida, C. J. Biagi, V. A. Rakov, M. A. Uman, D. M. Jordan, J. D. Hill, T. Morimoto, T. Ushio, Z. Kawasaki
4. Time-synchronized High-speed Video Images, Electric Fields, and Currents of Rocket-and-wire Triggered Lightning, EOS Transactions, AGU, Vol. 90 Fall Meeting Supplement, San Francisco, December 17, 2009, ID No. AE41A-03, C. J. Biagi, J. D. Hill, D. M. Jordan, M. A. Uman, V. A. Rakov
5. Compact Intracloud Lightning Discharges: Conceptual Mechanism, Modeling and Electrical Parameters (Invited), EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE32A-01, A. Nag, V. A. Rakov. Outstanding student paper award.
6. First Results from Airborne Detector for Energetic Lightning Emissions(ADELE) (Invited), EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE31A-05, D. M. Smith, J. R. Dwyer, B. Grefenstette, B. J. Hazelton, F. Martinez-McKinney, Z. Zhang, A. Lowell, N. A. Kelley, M. E. Splitt, S. M. Lazarus, W. Ulrich, H. Rassoul, M. Schaal, Z. H. Saleh, E. Cramer, X. Shao, C. Ho, S. A. Cummer, G. Lu, R. Blakeslee
7. Comparison of Thunderstorm Systems that Produce or Lack RHESSI Identified Terrestrial Gamma Ray Flashes, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE33B-0296, M. E. Splitt, D. E. Barnes, J. R. Dwyer, H. Rassoul, S. M. Lazarus, D. M. Smith, E. S. Cramer, M. Schaal, Z. H. Saleh, W. Ulrich, B. Grefenstette, B. J. Hazelton
8. A Ground-Based Campaign in Search of Terrestrial Gamma-ray Flashes associated with Thunderclouds and Lightning, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE33B-

0302, M. Schaal, J. R. Dwyer, Z. H. Saleh, H. Rassoul, S. M. Lazarus, M. E. Splitt, W. Ulrich, E. Cramer, D. M. Smith, B. J. Hazelton, B. Grefenstette

9. Positron Production During Realistic Runaway Processes Associated with Thunderstorms, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE33B-0307, J. R. Dwyer, D. M. Smith, H. Rassoul, E. S. Cramer, M. Schaal, Z. H. Saleh, B. Grefenstette, B. J. Hazelton, M. E. Splitt, S. M. Lazarus, G. J. Fishman, M. S. Briggs, V. Connaughton
10. On FDTD Modeling of Polarization of Conductors in a Uniform Electric Field, EOS Transactions, AGU, Vol. 90, Fall Meeting Supplement, San Francisco, December 16, 2009, ID No. AE21A-0304, Y. Baba, V. A. Rakov
11. A New Device Performing Optical Return Stroke Speeds in Lightning, International Union of Radio Science, USNC/URSI, January 8, 2010, Boulder, CO, R. C. Moore and R. Nuzzaci

III. Results

During Summer and Fall 2009, 34 rockets with trailing grounded wires were launched at the International Center for Lightning Research and Testing (ICLRT), 33 in the presence of negative charge overhead, 1 in the presence of positive charge overhead. There were 23 triggers of negative flashes to ground, 17 of the triggered flashes having return strokes (64 total strokes), the remainder of the flashes having only the initial stage composed of an upward positive leader followed by relatively continuous current at the 100 to 1000 Amp level for a hundred milliseconds or so. There were no triggers of positive flashes to ground. There was only one natural flash on site, and it was near the edge of the ICLRT. Overall, the lightning and thunderstorm activity during Summer and Fall 2009 in the vicinity of the ICLRT was below normal.

UF/FIT have continued the data collection and analysis of x-ray data from rocket-triggered lightning using plastic, NaI, and LaBr3 scintillation detectors correlated with high speed optical and electric and magnetic field measurements. Ten new plastic detectors and two new LaBr3 detectors have been installed in the system as part of the grant. Examples of the data taken during Summer and Fall 2009 are shown in Figs. 1- 5. Figure 1 shows sequential 4 μs frames of a dart stepped leader initiating the fifth stroke in the rocket triggered flash shown in Figure 3. In Fig. 1, space stems and space leaders are seen below and ahead of the primary leader channel, illustrating a mode of step development similar to that seen in laboratory sparks over 2 m in length and very poorly understood. Figure 2 shows x-ray emission, dE/dt radiation, and launch tower current to ground associated with each of the ten sequential 4 μs video frames of Fig. 1. Figure 3 shows a photograph of the full triggered flash from which the data of Figs. 1 and 2 are taken, in addition to some locations of dE/dt sources associated with the dart stepped leader and with the attachment process of that triggered flash. Figure 4 shows the slowly-varying electric field at two locations on the ground during three rocket launches as a function of triggering wire height. Figure 5 shows 3 μs frames of the initial development of an upward positive leader from the triggering wire.

UF has designed and constructed a prototype rf detector to detect rf pulses created by runaway electrons caused by cosmic rays passing through thunderclouds, potentially allowing a remote measurement of the static electric field in the thundercloud. While the detector operated reasonably, the relatively small signals for which we were searching were buried in ambient noise. To identify and measure their characteristics we will need to examine the signals only when cosmic ray showers are detected at ground. This has not yet been accomplished. Further, rf pulse measurements at multiple stations may be necessary to tease the signal from the inherent noise of the thunderstorm environment.

FIT has designed and constructed a prototype x-ray pin-hole camera using 30 NaI/PMT detectors and performed simulations to test the camera's performance during rocket triggered lightning. Based upon simulations, the pin-hole type x-ray camera appears to be feasible for the observation of the x-ray emissions from triggered lightning. A design has been developed that includes a practice way to hold a large number of PMT detectors and provides adequate shielding for operation at the ICLRT. FIT has continued to develop sophisticated Monte Carlo simulations and runaway electron transport models of Terrestrial Gamma Ray Flash (TGF), which are providing new information on radiation doses to individuals in aircraft.

IV. No patents were filed related to this research.

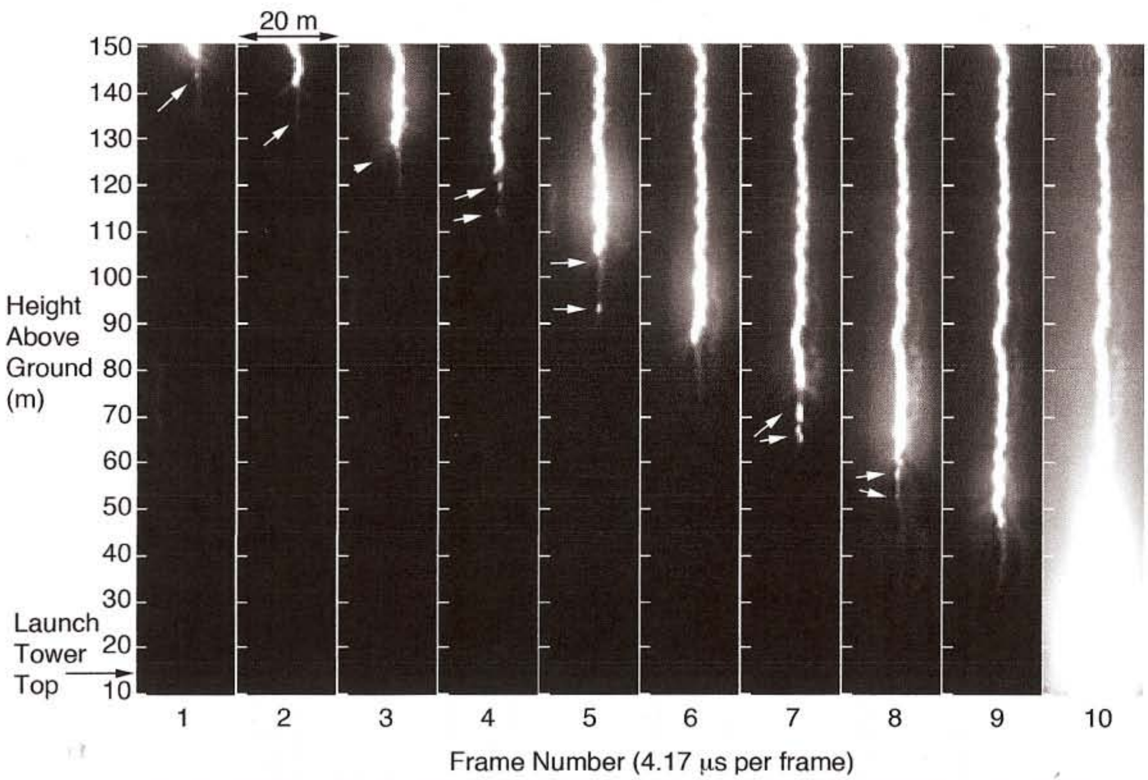

Fig. 1. Ten high-speed video frames (240 kfps, 4.17μs per frame) depicting the leader developing from 150 m height to the top of the rocket launch tower during a time of 41.7 μs. The top of the launch tower is 14 m above ground. The white arrows point to the luminous segments that formed separately from and below the downward-extending leader channel (some of them are too faint to be seen in this reproduction, but are readily identifiable in the original frames.) The return stroke began during frame 10.

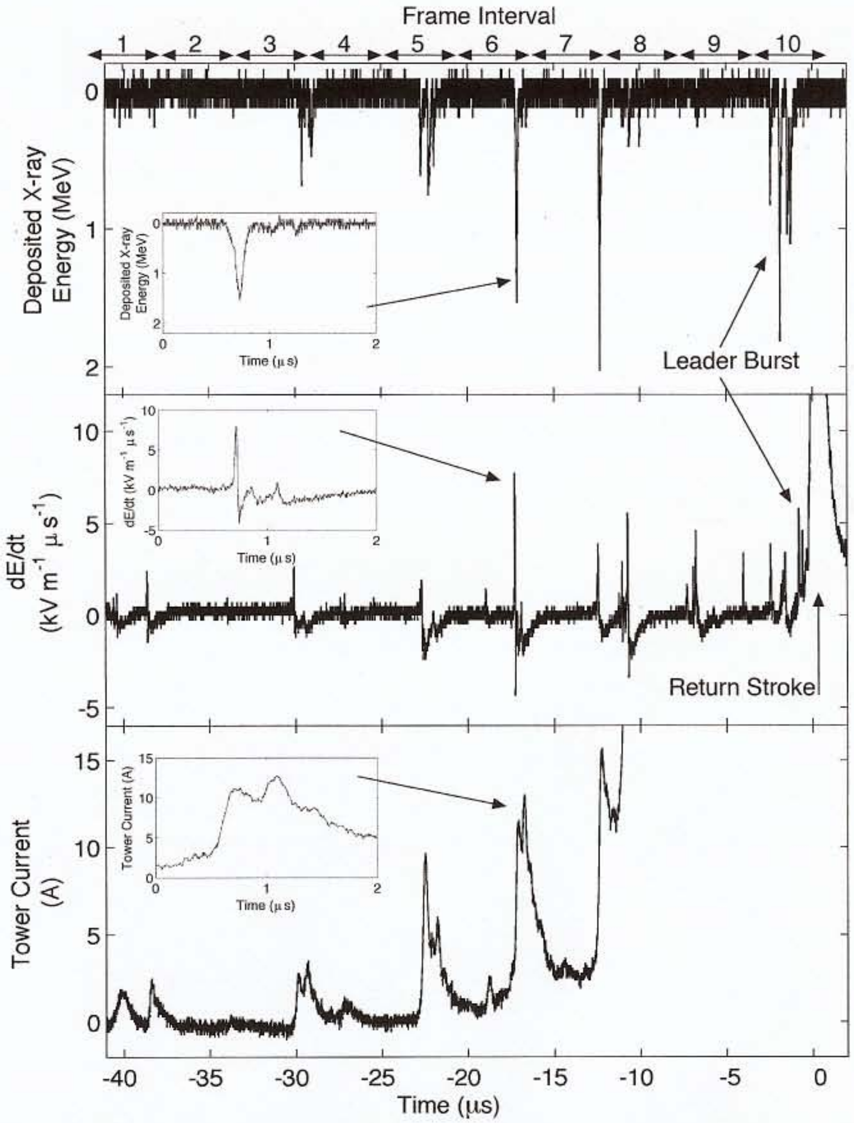

Fig. 2. The x-ray emission (top), dE/dt (middle), and tower current (bottom) displayed on a 42 μs time scale, recorded during the time when the 10 images shown in Fig.1 were recorded (frame intervals shown at top). The return stroke began at time zero. The insert plots show the pulses that occurred at -17 μs on a 2- μs time scale.

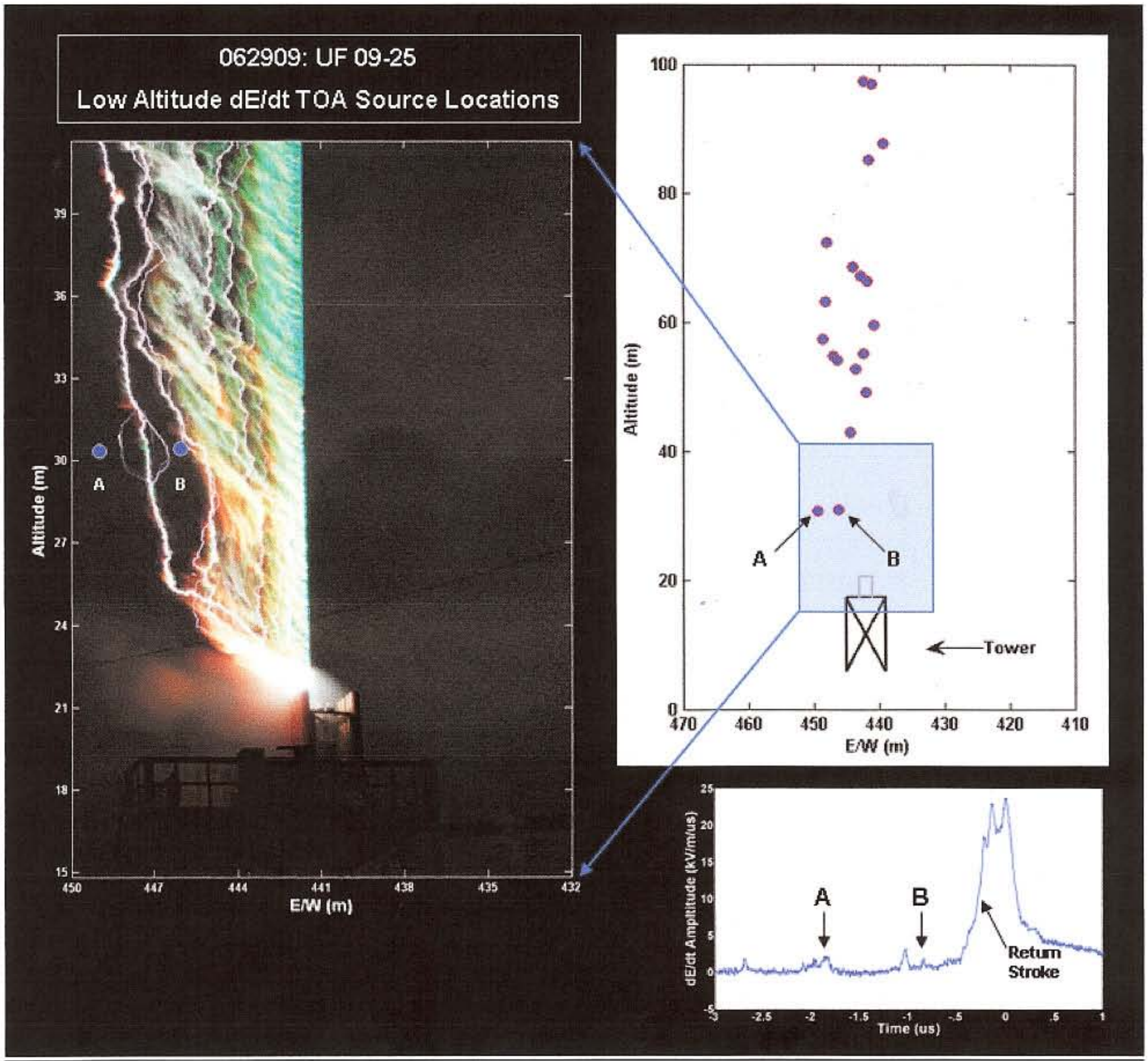

Figure 3. Lightning triggered as part of the UF/FIT Summer 2009 research at the ICLRT is shown in a 6 second exposure at left. The fifth stroke in the flash, shown at far left, was initiated by the downward dart-stepped leader shown in Fig. 1. The hypothesized connection between the upward and downward leader is the channel loop at the far left at 30 m height, 10 m above the launch tower top. Electric field derivative (dE/dt) pulses A and B, occurring at the start of the "slow front" process preceding the "fast transition" of the return stroke, are located with 3 m accuracy by the ICLRT's 8-station dE/dt TOA network and are clearly associated with the connection between the upward and downward leaders, part of the attachment process. Other dart-stepped leader dE/dt locations, up to a height of 100 m (locations were acquired to 1 km height), are shown at top right; 3 μs of the dE/dt recorded prior to the return stroke is shown at bottom right including pulses A and B. Similar and more detailed studies using these techniques including x-ray locations and characteristics are proposed.

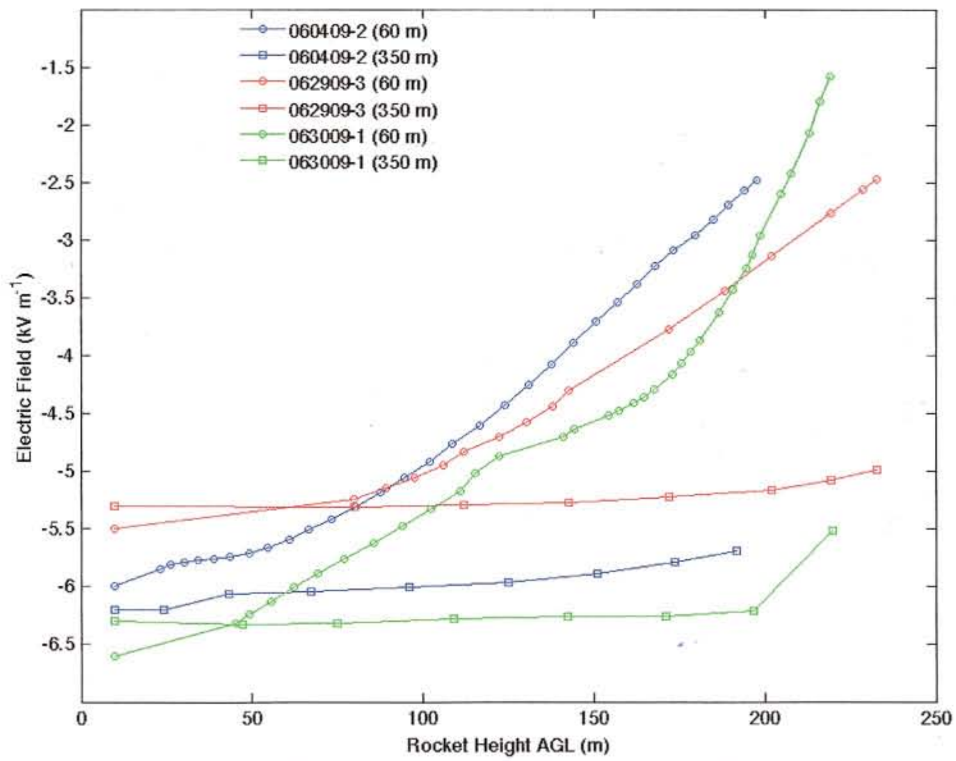

Figure 4. Three examples from ICLRT 2009 data of the electric field at ground level at horizontal distances of 60 m and 350 m from the location of the elevating, grounded triggering wire as a function of wire (rocket) height. The field at ground is increasingly shielded (becomes less negative) as the wire extends upward. With additional proposed measuring stations we will be able to calculate the ambient (before launch) electric field vs. height along the wire trajectory from the data measured at ground level. Note that the highest rocket altitude plotted is the height of sustained upward leader initiation, at which time the electric fields at ground level rapidly decrease and significant current flows at the channel base.

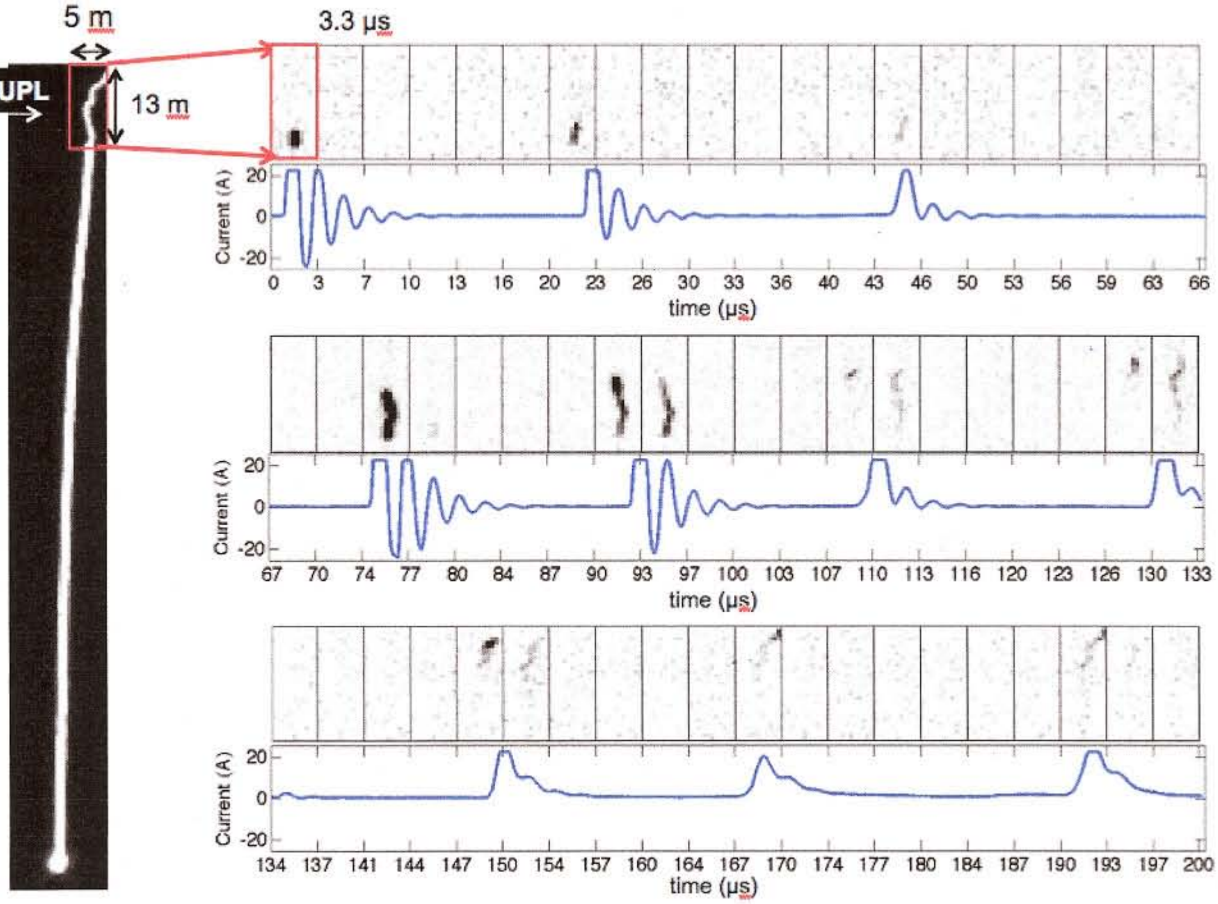

Figure 5. High-speed (3.3 μs frame time) optical measurements of the initial 13 m of a sustained upward positive leader and the correlated current at the channel base from 2009 ICLRT data. The current pulses from the first few leader steps are oscillatory, followed by unipolar current pulses and eventually a dc current level in the 100 A range. The figure at left shows the wire illuminated, which occurs tens of milliseconds after the optical and current data shown.